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Dynamic Virtual Resistance Droop Control Scheme for Distributed Generation System

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Abstract

The power quality of a low voltage distributed network is vulnerable to the plunge of a large number of distributed power sources, which could be at serious risk due to high circulating current. In order to overcome this problem, this paper proposes an active power-magnitude and reactive power-frequency droop control scheme for distributed voltage source inverters without a communication line. A novel dynamic virtual resistance control solution is demonstrated to minimize dynamic circulating current based on satisfied output voltage accuracy and stability. Differential and integral terms are added to the droop formulas to enhance the dynamic performance of the inverter and improve the stability for voltage magnitude and frequency. MATLAB simulations show that stable output voltage and small circulating current can be achieved in both grid connected mode and islanding mode by using the proposed scheme. This result is further verified by an experimental testing with two parallel voltage source inverters.

Keywords: *Distributed generation, dynamic virtual impedance, parallel inverter, droop control*

1. Introduction

Distributed Generation System (DGS) is one of the most important applications of both renewable energy and smart grid technology. Many distributed generators are connected to AC power grid through voltage source inverters (VSI) [1~3]. In order to power rational distribution and reduced circulating current among paralleled inverters, several control strategies, such as the PQ, VF, Droop, have been developed for application of paralleled distributed inverter [4~6]. However, PQ control strategy is not suitable for inverters working in Islanding Mode [4] and VF control strategy requires high quality communication and mode swift technique [5]. The Droop strategy is a voltage-source-peer control method and it has the advantages of stable Islanding Mode without communication line, rational current distribution and high redundancy. Therefore, it is suitable for distributed generation systems [6~9]. Georgakis proposed a Droop strategy for VSI inverter, however, the big inductance on the output deteriorates both the accuracy and efficiency of load voltage [7]. Yun studied the model to calculate the relationship between the ideal droop line and practical droop line for reactive power-magnitude, but this model requires precise parameters which are difficult to measure [8]. Ahn proposed a multi-stage gradient method for droop control to improve the output accuracy and response speed, but it is not clear how the gradient of each stage is decided [9]. Virtual impedance strategy was proposed in recent years and it is generally considered as an effective method to reduce the circulating current, however, the stability of this method should be improved [10~12].

In this paper, we propose a novel dynamic virtual resistance control based on droop control for distributed VSI inverters in low voltage generation system. The output effective impedance of the inverter can be considered as a resistor with adjustable feedback coefficient, and this simplified droop model is suitable for low voltage distribution networks, of which resistance is much larger than its inductance. In this study, the influence of virtual impedance and droop algorithm to the stability of inverter will be analyzed, and a novel dynamic virtual impedance method is proposed to improve the stability and output performance. This paper is organized as followed. We firstly study the stability of the droop algorithm under dynamic virtual impedance in section 2. Then we introduce the adjustment principle and design of dynamic virtual impedance parameters in section 3.1. In section 3.2, we demonstrate the steady state

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recovery design of droop line. In section 4, MATLAB simulation results are shown for the proposed theory, and practical experiment is carried on with two single-phase voltage source inverters to further verify the methods.

2. Scheme of the Dynamic Virtual Resistance Droop Control of VSI

A typical Droop control schematic diagram of a VSI is shown in Figure1. For most of the VSI, the droop line algorithm uses active power-frequency and reactive power-magnitude relationships, and therefore the output inductance of the inverter is generally larger than the resistance. However, for a low voltage distribution network, the resistance is far larger than the inductance [13], which limits the output voltage control for VSI and the deviation of voltage is increased. If the output impedance of the inverter can be replaced with a resistance, the load voltage stability will be improved and droop control can be simplified.

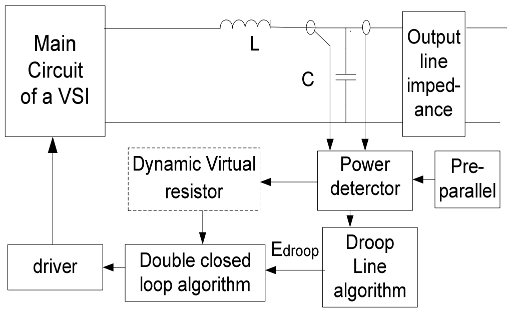


Figure 1. Droop control schematic diagram of a VSI

The virtual impedance of an inverter is used to reduce the influence of nonlinear load current and dynamic circulating current, and it can be represented as a series of voltage source and impedance according to Theremins law,

$$U_o = G(s)E_{droop} - z_{virtual}(s)I_o \tag{1}$$

In Equation 1, the inverter output voltage U_o consists of the voltage E_{droop} given by the droop module and the voltage transfer function *G(s).* The transfer function $z_{virtual}(s)$ is the virtual impedance of the inverter, and it can be adjusted by changing the feedback coefficient in dashed line box in Figure 1. After a fine adjustment, $z_{virtual}(s)$ becomes a pure resistor far bigger than the impedance of a distribution network. This virtual resistor will greatly help to improve the voltage stability and lower the circulating current in inverters. The detailed adjusting design will be explained in section 3.

When the output impedance becomes to a resistor, the relationship between output power and output voltage of inverter can be decoupled into two independent parts. They are active power-voltage magnitude and reactive power-voltage phase. Therefore the droop algorithm can be described as the power regulation relationship, such as,

$$V_i = V_N - m_i P_i \tag{2}$$

$$\omega_i = \omega_N + n_i Q_i \tag{3}$$

In the above equations, U_i is the output voltage amplitude of the i_{th} inverter, ω_i is the frequency of the i_{th} inverter, U_N and ω_N are the rated voltage and rated frequency of inverter, P_i and Q_i are the output active power and reactive power of the i_{th} inverter, m_i and n_i are the droop coefficient of the i_{th} inverter.

However, the final output of inverter is influenced by both virtual resistor and droop coefficient. Figure 2 is drawn to explain their roles in this virtual-impedance-droop system. Because the virtual impedance is a resistor, it only influences the output voltage magnitude and not change output phase. So this analysis is focused on the droop line of active power-voltage magnitude. In Fig.2, the dotted line 1 presents the given droop line of active power-magnitude module. This given voltage E_{droop} will change to the output voltage V_o after passing through the virtual impedance control loop. According to equation 1, the increase of output power will lead to the increase of the voltage droop on the virtual impedance $z_{vitrual}$ with a coefficient k. It is clear that the final output droop gradient is bigger than the given droop line 1, as dotted line 2 shows. Its equation is

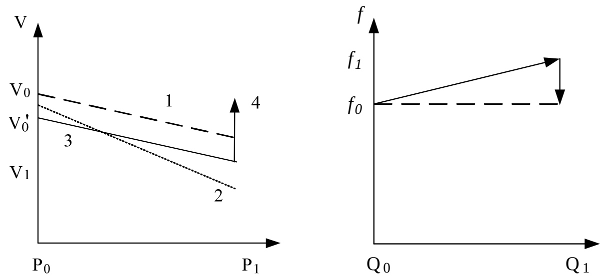


Figure 2. Control diagram of virtual-impedance-droop

$$V_{oi} = V_N - (m_i + k)P_i \tag{4}$$

The steeper the droop gradient is, the lower the inverter's stability will be [5]. What's more, this may produces that the load voltage is lower than the minimum limits required when the load is heavy. If the total voltage droop on $z_{vitrual}$ and $G(s)$ dose not change with the output power, the closed loop stability will be better and this can be achieved by dynamic adjusting $z_{vitrual}$. The final output droop line of inverter is shown using line 3 and it parallels with the given droop line 1. In this case, the stability will be guaranteed and the equation of active power-magnitude droop line 3 is as follow.

$$V_{oi} = (V_N - V_C) - m_i P_i \tag{5}$$

Further more, the steady state voltage deviation V_c of equation 5 can be compensated using an optimized algorithm, which takes a integration of the deviation. Then the droop line will rise after the output power gets stable, as line 4 shows.

3. Design of the Dynamic Virtual Resistance and Droop Control for VSI

3.1. Design for the Dynamic Virtual Resistance Parameters

A closed loop model of a virtual-impedance-control inverter is illustrated in Figure 3. In this figure, K_1, K_2 and K_3 are the adjustable coefficients and K_1 is the dynamic adjustable coefficient [10].

The transfer functions of the virtual voltage source and virtual impedance can be deduced as followed, such that,

$$\begin{aligned} G(s) = {} & K_2R(Ps+I)/[RLCs^3 + (L + rRC + K_1K_2RC + K_2K_3PRC)s^2 \\ & +(K_2RP + K_2K_3CRI + R + S)s + K_2RI] \end{aligned} \tag{6}$$

$$Z_{virtual}(s) = \frac{(K_2K_3PR + K_1K_2R)s + K_2K_3RI}{RLCs^3 + (L + rRC + K_1K_2RC + K_2K_3PRC)s^2 + (K_2RP + K_2K_3CRI + R + S)s + K_2RI} \tag{7}$$

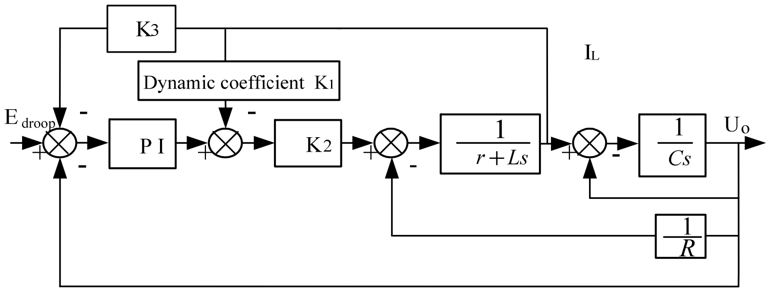


Figure 3. Controller module of virtual impedance

For the prototype inverter studied in this paper, the main circuit parameters are listed such that, the inductor: L=2mH; the capacitor: C=0.3μF; the connect line resistor: r=0.6Ω; and the load: R=50. It can be seen that the phase of the virtual impedance is close to 0 degree in 50Hz when $P=15$, $I=6$, $K_2=2$, $K_3=0.2$, and $20<K_1<40$, which mean that the virtual impedance can be a resistor and it satisfies the above decoupled control conditions.

Then the dynamic adjustment algorithm of K_1 can be deduced according to the analysis of Equation 5, and it is hoped that the equation $G(s)*E_{droop}-Z_{virtual}(s)*I_o=E_{droop}-V_c$ can be realized by the dynamic virtual resistance. The maximum V_c corresponds to the maximum value of the output voltage deviation permitted when the inverter is in full load. So, the dynamic virtual impedance $Z_{virtual}(K_1)$ should be adjusted to satisfy the following equation, such that,

$$Z_{virtual}(K_1) = \frac{(1-G(s))E_{droop} - V_C}{I_o} \tag{8}$$

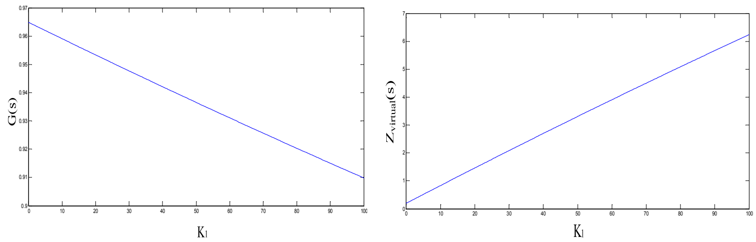


Figure 4. Transfer function of $G(s)$ & $Z_{virtual}(s)$ with K_1

It is noted that, the magnitudes of $G(s)$ and $Z_{virtual}(s)$ can be adjusted by changing the value of K_1 during the period of fundamental voltage wave. Figure 4 shows the curve of $G(s)$-K_1 and the curve of $Z_{virtual}(s)$-K_1 according to Equations 6-7. It is clear that these curves are close to linear function when K_1 varies in a certain range. So these two curves can be approximated by linear equations such that,

$$G(s) = AK_1 + B \tag{9}$$

$$Z_{virtual}(s) = CK_1 + D \tag{10}$$

Based on Equation (8), (9), and (10), the dynamic coefficient K_1 can be written as,

$$K_1 = (V_{C\max} - DI_0 - (1-B)E_{droop})/(CI_0 - AE_{droop}) \tag{11}$$

The dynamic adjusting coefficient K_1 will help to stabilize the output voltage and reduce the circulating current as well as keeping the inverter stable. Based on the main circuit parameters and control loop parameters of the above distributed inverter, the inverter's stability can be analyzed by the root locus method, and K_1 varies from 20 to 40 with the interval of 4. The root locus is also shown in Figure 5. From Figure 5, we can see that this inverter is a three-order system, whose one Zero and one Pole are too close to each other. One couple of Poles is close to the real axis and they are far away from Zeros while K_1 increases, which means that the oscillation will diminish and the inverter will be stable.

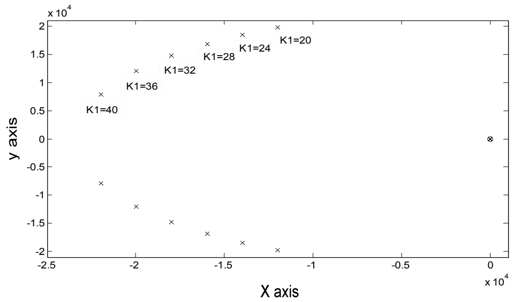


Figure 5. Tendency plots of pole-zero of inverter

3.2. Design of Droop Control Parameter

These paralleled inverters achieve their rational power distribution by changing their output voltage magnitude and frequency respectively according to their droop lines. However, the gradients of droop lines should be selected carefully. The system is easily to unstable when the droop gradient is too big. But the circulating current among inverters will be bigger when the droop gradient is smaller. In this paper, the gradient parameters of droop lines are estimated according to the rated output power and maximum deviations permitted of voltage magnitude and frequency. They are listed as follows.

$$m = \frac{V_N - V_{\min}}{P_{\max} - P_N} \tag{12}$$

$$n = \frac{f_{\max} - f_N}{Q_{\max} - Q_N} \tag{13}$$

From equation 11 and 13, it is easily to see that the gradient of frequency droop line is more smaller than that of magnitude droop line. This will lead to a longer adjustment time to get frequency stability. So the design of the droop line of the reactive power-frequency should be improved and a differentiation element can be brought in to enhance dynamic response speed.

In addition, there is a stable deviation if the dynamic virtual resistance method is only used in Fig.2. This means that the steady voltage magnitude and frequency of load will deviate more from rated value when active-power or reactive-power increases. So, two integration elements are brought into the droop lines design of active power-magnitude and reactive power–frequency to recover the voltage accuracy after the power distribution process. These equations are as follows.

$$V_{oi} = V_N - m_i P_i + a_V \int (V_N - V_{oi}) dt \tag{14}$$

$$\omega_{oi} = \omega_N - n_i (1 + k_{if} s) Q_i + a_f \int (\omega_N - \omega_{oi}) dt \tag{15}$$

In above equations, a_V、 a_f are the integral coefficients for voltage deviation. The integral coefficients are small, they have little influence on the dynamic adjusting during the period of power distribution. After the power distribution is over, the voltage magnitude and frequency deviation will appear. The droop lines will change in the antagonistic direction as the integration elements starts to play more and more important role. The magnitude and frequency of voltage will recover in static state finally. k_{if} is a differential coefficient of frequency droop line, which makes the dynamic response better for the droop gradient is small.

4. Simulation and Experiment Results

4.1. Simulation Result and Analysis

In order to verify the proposed dynamic virtual resistance and droop control strategy, a MATLAB/SIMULINK simulation model of two single-phase parallel inverters is developed. Figure 6 shows a circuit structure that two inverters provide power to a joint load in parallel. The main structure of a VSI model developed is similar to the circuit in Figure 1, and the MATLAB model consists of the main parallel circuit, the load module, the power computation module, the droop module and the virtual impedance controller.

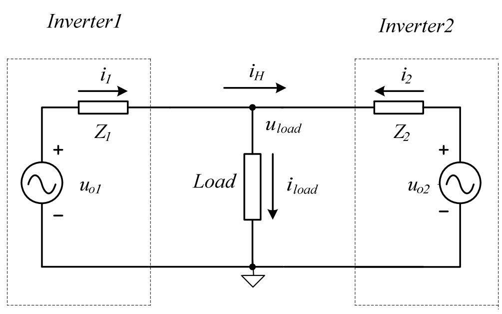
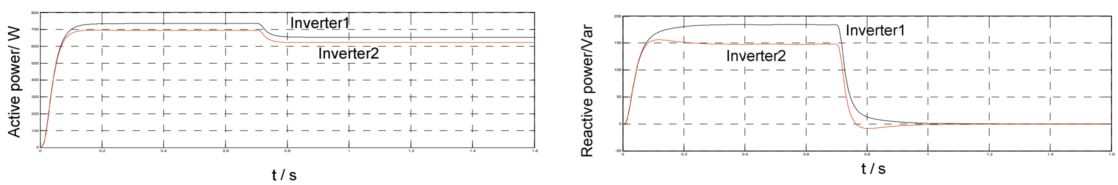
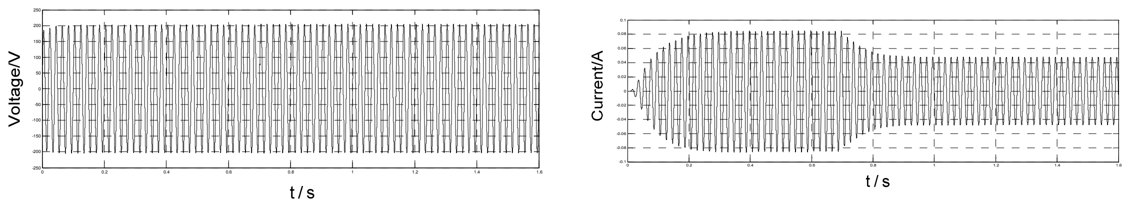


Figure 6. Two inverters in parallel

The capacity of the two inverters is both 1kVA/220Vac and the main model parameters are set as, the inductor: L=2mH; the resistance of L: r_L=0.2Ω; the capacitor: C=30μF; and the output line impedance: Z=0.32Ω. The droop parameters are list such as, m_1=0.0044, n_1=0.001, m_2=0.00352, n_2=0.0008, a_v=a_f =0.016, and k_{if} =0.005. Figure 7 shows the simulation results, in which the output power of the two inverters is shown with the load active power of 1.7kW and the load reactive power of 0.4kW. After 0.7s of starting, the load active power is cut off at 0.4kW and the load reactive power is cut off at 0.4kW.



(a) Output active power of two inverters (b) Output reactive power of two inverters



(c) Load voltage waveform (d) Circulating current among inverters

Figure 7. Dynamic state waveform of dynamic virtual resistance and droop control simulation

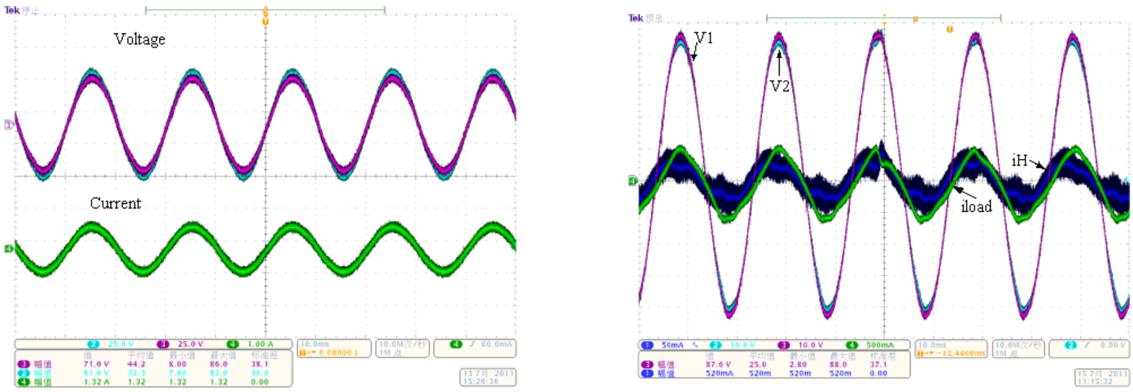
It can be seen from Figure 7 that these two inverters have distributed their reactive power and active power according to their droop line gradients very efficiently in the simulation.

The load voltage is stable with very small deviation, and the circulating current is about 0.8A in full load. Besides, the circulating current falls by 40 percents when the load is cut off by 30 percents. It indicates that the diminishing circulating current of dynamic virtual impedance is functioning properly. The simulation results show that the dynamic virtual impedance droop strategy is efficient in power distributing, voltage accuracy and circulating current diminishing, and it is very useful for a distributed generation system with many paralleled inverters.

4.2. Experiment Results and Analysis

Two 1kVA single-phase full bridge inverters are developed to test the proposed algorithm. The switching frequency of the inverter is set at 10 kHz and a TI TMS320F28335 DSP is used as the controller.

Because the number of solar panels available is limited, the DC input voltage of the inverter is tested only under $60V_{DC}$. In this case, the normal output voltage of inverter is set at 45V/50Hz. There are two main stages in this experiment, the first of which is to test the inverter's independent performance. Figure 8(a) shows the output voltage and current waveforms of the inverter, and it shows that the output waveform is very close to a sine wave with only a little distortion. When these two inverters supply a joint load in parallel, the load voltage waveform with the load current and the circulating current i_H between the two inverters is shown in Figure 8(b). It can be seen that the parallel structure of the two inverters achieves better performance by generating a more perfect sine wave in the load voltage and load current, an the circulating current can be ignored comparing to the value of the load current.



(a) Inverter's output voltage/current during parallel (b) output voltage/current & circulating current

Figure 8. Waveforms of experiment

5. Conclusion

In this paper we proposed a novel dynamic virtual resistance and droop control strategy for distributed generation systems without a communication line. The virtual resistance simplifies the relationship among active power, reactive power, voltage magnitude and voltage frequency. This strategy offers good stability, small output voltage deviation and small circulating current. The fundamental theory of this strategy was introduced, and the dynamic coefficient calculation method is also deduced in detail. Integration elements are introduced into the droop line equations to recover the magnitude and frequency of load steady voltage, and a differentiation element is also applied to enhance the frequency response. From both MATLAB simulation and real prototype testing we can see that this novel control strategy is useful and effective.

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